DAMAGE DETECTION OF UHP-FRC PLATES USING RANDOM DECREMENT TECHNIQUE

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ABSTRACT

This paper is about structural health monitoring using Random Decrement (RD) technique for Ultra High Performance Fiber Reinforced Concrete (UHP-FRC) slabs. Five simply supported slabs with identical dimensions are tested using low-velocity impact technique. Multi-impact load is applied at the mid-point of the UHP-FRC slabs by dropping a 475 kg steel weight from a constant height of 4.15 m. Two parameters are considered: namely: the steel reinforcement ratio, and the steel fiber volume content. The natural frequencies (eigenvalues) and corresponding mode shapes (eigenvectors) of tested plates are extracted numerically using linear perturbation analysis available in ABAQUS (Lanczos solver) to verify the experimental values extracted using RD signatures. The dynamic behavior (natural damped frequencies and damping ratio) of intact slabs and after applying the impact load is determined. The random decrement signatures are extracted and compared at intact and damage state. RD technique is used successfully to extract the dynamic characteristics of tested slabs with reasonable accuracy. Changes in dynamic parameters identify the existence and intensity of damage. As additional results, it is observed that steel fibers enhance the vibration behavior of slabs and the mobilization of reinforcements cause a noticeable change in natural frequency.

Keywords: Structure health monitoring, drop-weight impact, Random Decrement, damping ratio, natural frequency, and Ultra High Performance Fiber Reinforced Concrete (UHP-FRC)

1. INTRODUCTION

Damage detection using RD technique was originally deployed for aerospace industry to detect damage in aerospace structure surface. Random decrement is considered as a time domain procedure. The aim of the project was to determine the dynamic response of space structure exposed to ambient loads and vibrations. The concept focuses on the dynamic signature and damping detection to monitor the probable damage of structure during its service life. The ambient vibration analysis encounters numerous auto correlation functions to detect damage. In the early days, it was recognized that the envelope of autocorrelation functions can be used to define the main dynamic properties of structure (natural frequency and damping ratio).

Natural frequency and damping ratio are varied by both damage and load variations. In order to detect damage, there was a need to eliminate the response to load variations. This led to introduction of random decrement technique which is based on output measurement approach. The response of a system to random input loads is, in each time instant t, composed by three parts: the response to an initial displacement; the response to an initial velocity; and the response to the random input loads between the initial state ant the time instant t. Through averaging a large number of time segments of the response with the same initial condition, the random part of the response fade out from the average, and free decay response will be obtained (Asayesh et al. 2009).

Noise reduction is another advantage of RD technique. The free decay response pattern is directly related to the dynamic parameters of the system. This pattern which is the result of averaging is well known as Random Decrement Signature (RDS). Damage effects on the dynamic parameters of the structure such as: mass, moment of inertia, and stiffness. Change in dynamic parameters cause the RDS to be different. RD technique is a promising technique for long term monitoring of the structures health by keeping track of RD signatures (Rodrigues & Brincker 2004).

In this research paper an experimental investigation has been conducted to develop more understanding of applying random decrement to detect damage existence and its intensity in UHP-FRC slabs. Drop-weight impact is used to cause the damage and the response to random loads of impact hammer is gathered by accelerometer. Also, the results are validated using finite element analysis.

2. RANDOM DECREMENT (RD) TECHNİQUE

Random Decrement (RD) technique is a time domain non-destructive testing procedure, with aim of obtaining free decay response under any service load conditions. RD signature is equivalent to free decay response which its changes indicate the damage. RD technique is based on output measurements identification with considering theoretical facts.

Normalized equation of the motion relative to the mass, Equation 1 is:

[1] $$\ddot{x}(t)+2\omega_o\xi\dot{x}(t)+\omega_o^2 x(t)=f(t)$$

Where x (t) is displacement vector of the system.

By contributing Probability Theory to the equation of motion, the equivalent free decay response can be derived by Equation 2:

[2] $$\ddot{\mu}+2\xi\omega_o\dot{\mu}+\omega_0^2\mu=0$$

Where μ is the mean value of the displacement which also can be shown by vector $\bar{x}$.

Equation 3 is the solution for the μ which is called Random Decrement function XR (τ):

[3] $$X_{Ri}(\tau)=\frac{1}{N}\sum_{i=1}^{N}xi(ti+\tau)$$

RD is an averaging process of time history segments xi (ti + τ) of random vibration responses that exceed certain triggering condition ti and N is the number of triggering points (Elshafey et al. 2011). Types of triggering points are level crossing, positive points and zero crossing with positive slope. Noise will be reduced by considering more triggering points. The triggering level interval has to be within the standard deviation of the response positive points and 2.5 times the standard deviation of the response (Sim et al. 2011). The technique used to extract the damping ratio is Logarithmic Decrement and basic frequency is obtained from the free decay curve (Morsy et al. 2015).

The frequency is calculated as inverse of the average period of one cycle (T) on the RD curve, Equation 4:

[4] $$f_r=\frac{1}{T}\ \text{Hz} \quad \text{or} \quad \omega=\frac{2\pi}{T}\ \text{Rad/Sec}$$

In order to find damping ratio, first the logarithmic decrement (δ) is found as Equation 5:

[5] $$\delta = \frac{1}{n} ln\left|\frac{A_i}{A_{i+n}}\right|$$

Where A_i is the amplitude of cycle i and A_{i+n} is the amplitude of cycle i+n of the RD curve.

Secondly, the modal damping ratio ξ is obtained as Equation 6:

[6] $$\zeta = \sqrt{\frac{\delta^2}{4\pi^2 + \delta^2}}$$

3. TEST SPECIMENS

Five reinforced UHP-FRC slabs with identical dimensions are constructed and tested under drop-weight impact. The plates are 1950 mm square with a thickness of 100 mm. All slabs are doubly reinforced with equal top and bottom orthogonal steel reinforcement mats to resist the tensile stresses generated due to reverse moment after bounding. Two parameters are investigated namely: steel reinforcement ratio (0.47, 0.64, and 1.00% per layer/direction); and steel fibers volumes contents (1, 2, and 3%). Details of UHP-FRC slabs and the studied parameters are presented in Table 1.

Table 1: Details of UHP-FRC slabs

Series No.	Specimen[1]	Fiber Content (%)	Reinforcement Ratio[2] (%)	Reinforcement Spacing (mm)
1	UF_1S100	1	1.00	100
2	UF_2S100	2	1.00	100
3	UF_3S100	3	1.00	100
4	UF_2S158	2	0.64	158
5	UF_2S210	2	0.47	210

[1]Plates' identification: fiber fibre content (F_1=1%, F_2=2%, F_3=3%); spacing (S_{100}=100, S_{158}=158, S_{210}=210mm).
[2]Based on total section height = 100 mm, per layer; per direction.

The used UHP-FRC mixes are Ductal® commercially available in North America marked by Lafarge Canada (Lafarge, 2015). All UHP-FRC mixes have target 28-day cylinder compressive strength of 150 MPa. All mixes have identical mix proportions with exception of fibre volume dosage. Identical short steel fibers with a nominal diameter of 0.2 mm and 13 mm long are used in all UHP-FRC mixes. The fiber manufacturer's specified minimum tensile strength and elastic modulus of 2,600 MPa and 205 GPa, respectively. CSA standard steel bars 10M of Grade 400 are used as longitudinal reinforcement in all slabs (CSA, 2004). The tested geometrical and materials properties of UHP-FRC materials are summarized in Table 2. Each data point in the table is averaged from three specimens.

Table 2: Properties of UHP-FRC materials

Fiber ratio (%)	Density (ρ) kg/m^3	Compressive strength (f_c') MPa	Strain at peak stress (ε_0) mm/m	Splitting tensile strength (f_{tsp}) MPa	Elastic modulus (E_0) GPa	Poisson's ratio (υ) ---
1	2600	154.80	4.10	7.30	45.00	0.2
2	2650	162.40	4.35	11.10	45.80	0.2
3	2710	158.70	4.50	14.00	46.30	0.2

4. DROP-WEIGHT IMPACT SET-UP

The drop-weight impact test setup has been designed and fabricated at Ryerson University with a target capacity of 19.30 kJ (Fig. 1). All slabs are tested under same loading and supporting conditions. Slabs are subjected to hard impact at their mid-point and simply supported at their four corners. The uplift of plates' corner is prevented by using a special tie-down steel frame which allows a sufficient amount of rotation up to 5º. A tower frame is used to guide the drop-weight to ensure hitting the plates' mid-point. The striking surface of the steel drop-weight is flat with dimensions of 400×400 mm.

The experimental investigation is equipped with sophisticated instrumentation to monitor specimen deflection, accelerations, reinforcing bar strains, and applied impact loads. The output data are recorded using a digital dynamic data acquisition system ECON model MI-7008 with sampling rate of 100 kHz. More details regarding this impact setup and used instrumentation can be found elsewhere (Othman & Marzouk 2015).

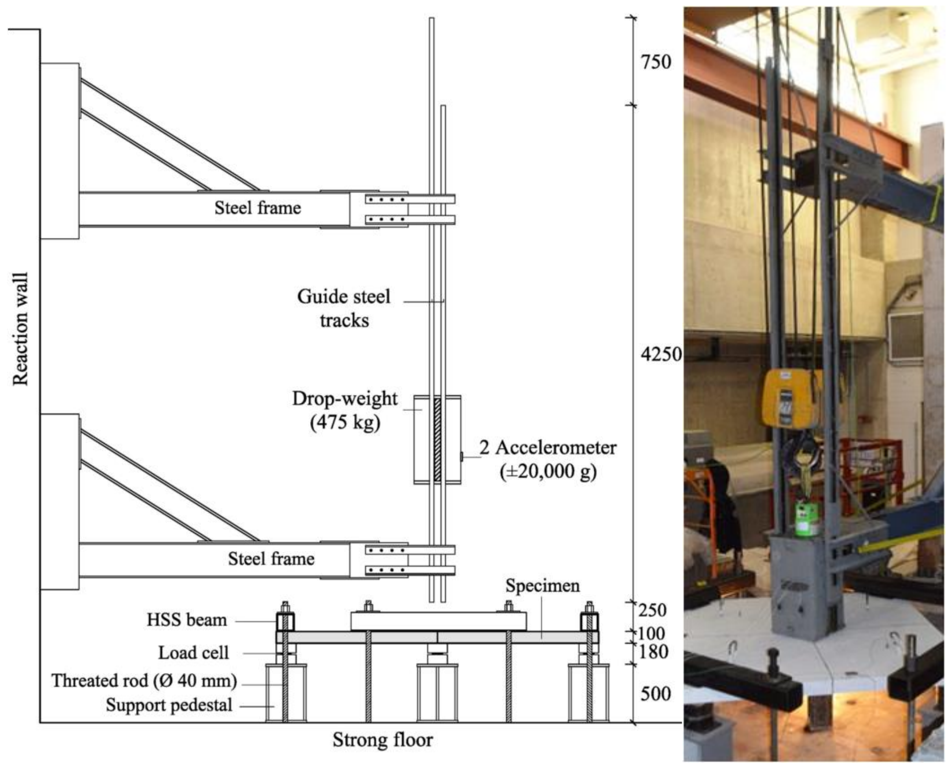


Figure 1: Details of drop-weight impact test setup (dimensions in mm) (Othman & Marzouk 2015)

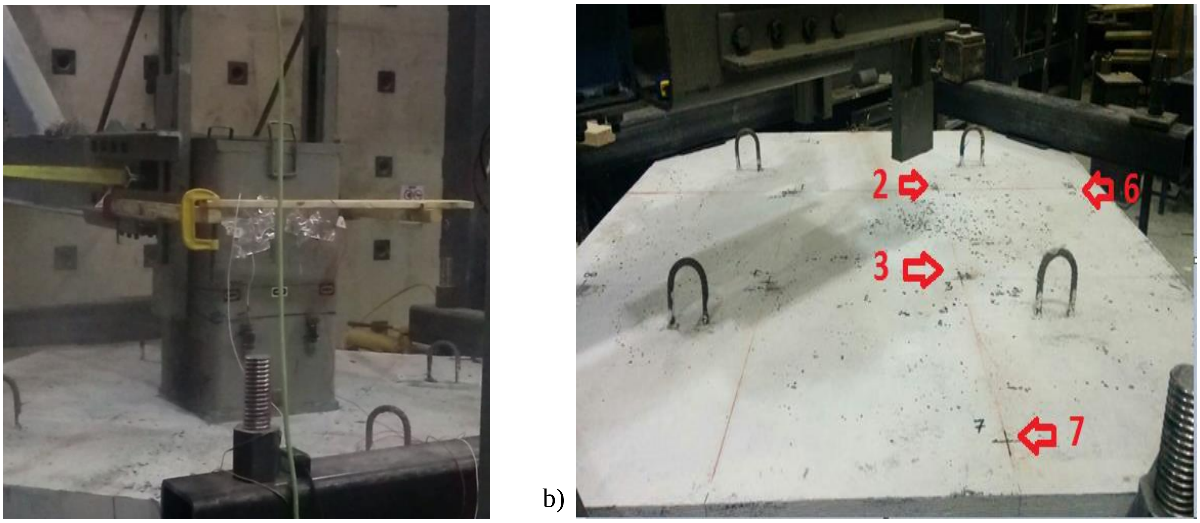
a) 

Figure 2: Test site a) Impact load view b) Locations of accelerometer

Figure 3: Random decrement test equipment

5. RANDOM DECREMENT TEST EQUIPMENT

Random excitations were applied on slabs using a 0.5 Kg impact hammer type Kistler 9728A with sensitivity of 1.05mV/LbF. The response was captured using 50 g accelerometer type Kistler 8640A50 with sensitivity of 102.5 mV/g, and the data acquisition system used was compact DAQ-NI-9184 with four channels (Fig. 2 &3).

6. VALIDATION OF IMPLEMENTED RANDOM DECREMENT TECHNIQUE

This stage of analysis is intended to verify the use of RD technique to extract the dynamic properties of UHP-FRC slabs. The natural frequencies (eigenvalues) and corresponding mode shapes (eigenvectors) of tested plates are extracted numerically using linear perturbation analysis available in ABAQUS (Lanczos solver). Eight node continuum brick elements with reduced integration (C3D8R) are used to model concrete. Longitudinal steel reinforcement is modelled using two node beam element (B31) using same arrangement and dimensions as tested plates. The B31 element uses linear interpolation and has a constant stress. Full details of the elements formulation can be found elsewhere (Simula 2015). The embedded constrain is used to simulate bond between reinforcement and surrounding concrete assuming full bond. Only supporting system parts in direct contact with specimens are modelled to simulate their effect on test specimens and in same time reduce the computational cost of the analysis. The three dimension FE model of the test setup is shown in Figure 4.

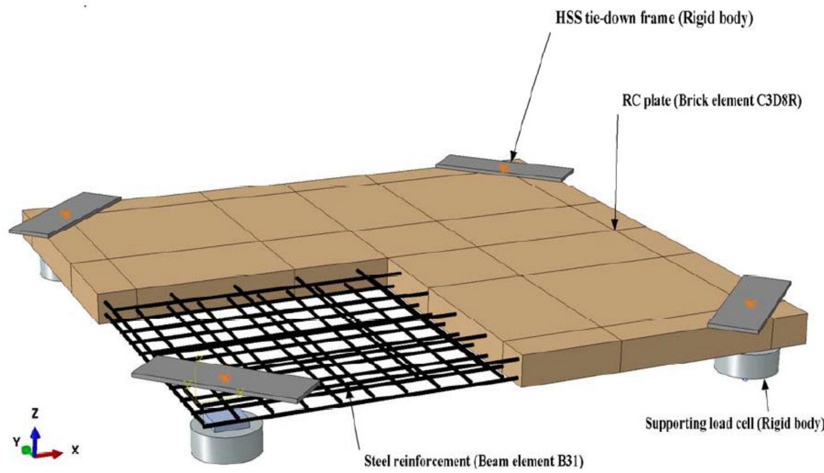


Figure 4: Generated finite element model of UHP-FRC slabs

In Modal analysis, density of material must be defined in order to form the lumped mass matrix. Additionally, the elastic behavior of material is specified by defining elastic modulus and Poisson's ratio. The geometrical and material properties of UHP-FRC used in the FE-model are extracted from the results of material tests presented in Table 2. Figure 5 shows typical first mode shape of modeled plate. Table 3 shows the comparison between fundamental natural frequencies extracted numerically and experimentally for all tested plates. It is evident from this table that, the fundamental natural frequencies of the finite element model and the actual model are in good agreement with maximum difference less than 6% in all plates. This indicates that RD technique can be used to extract the dynamic properties of UHP-FRC plates accurately in subsequent analyses.

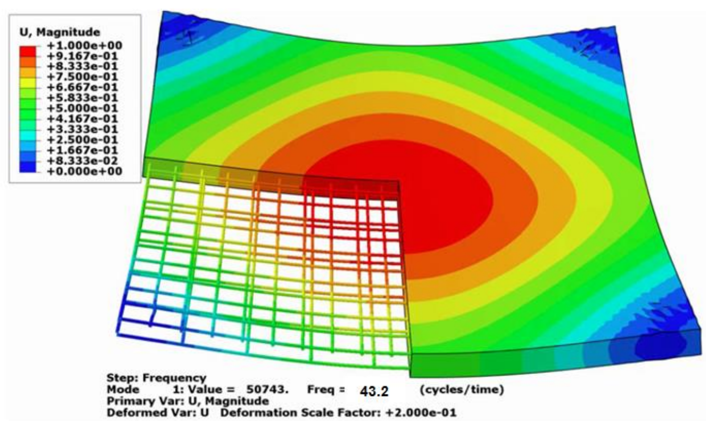


Figure 5: First model shape of plate UF_1S100 (f = 43.22 Hz)

Table 3: Comparison between numerical and experimental fundamental natural frequency

Plate ID.	Numerical Hz	Experimental Hz	Difference (%)
UF_1S100	43.22	45.00	4.10
UF_2S100	44.20	42.00	5.20
UF_3S100	44.60	42.5	4.90
UF_2S158	44.10	43.0	2.55
UF_2S200	43.65	---	---

7. RESULTS

The vertical accelerations were measured at sampling rate of 2500 Hz on four slabs in four locations (points 2, 3, 6, & 7) in three stages including intact, after first and second impact drops. RD signature was computed using accelerometer data with triggering level equals to the 1.4 times the standard deviation of the captured response. Figure 6 presents the extracted RD signature of point 3 for slab 3. Integration is conducted using a time increment of 0.0004 sec and the number of segments used to construct the RD is equal to half of the triggered data number.

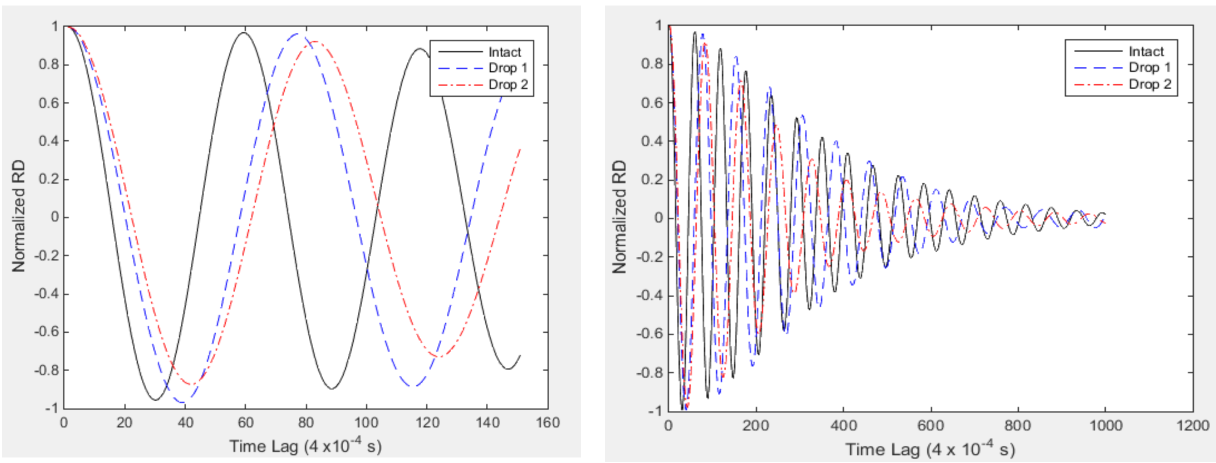


Figure 6: Mode 1, Normalized random decrement signatures for slab 3 point 3 with different impact loading (intact, first and second drop)

The results for damping ratio found by logarithmic decrement and natural frequency are shown in the tables 4 and 5 and following bar graphs (Fig. 7 & 8).

Table 4: Mode 1, damping ratio for four slabs at four points (2, 3, 6 &7)

Slab #	Point 2 Intact	Point 2 1st Drop	Point 2 2nd Drop	Point 6 Intact	Point 6 1st Drop	Point 6 2nd Drop	Point 3 Intact	Point 3 1st Drop	Point 3 2nd Drop	Point 7 Intact	Point 7 1st Drop	Point 7 2nd Drop
1	3.2	3.6	3.8	3.2	3.6	3.8	3.2	3.6	3.8	3.2	3.5	3.8
2	3.2	3.5	3.7	3.1	3.5	3.8	3.1	3.5	3.8	3.0	3.5	3.8
3	3.2	3.65	4.3	3.2	3.7	4.3	3.2	3.5	4.3	3.2	3.6	4.3
4	3.3	4.3	4.5	3.3	4.5	4.8	3.3	4.5	4.9	3.3	4.6	4.8

Table 5: Mode 1, natural frequency for four slabs at four points (2, 3, 6 &7)

Slab #	Point 2 Intact	Point 2 1st Drop	Point 2 2nd Drop	Point 6 Intact	Point 6 1st Drop	Point 6 2nd Drop	Point 3 Intact	Point 3 1st Drop	Point 3 2nd Drop	Point 7 Intact	Point 7 1st Drop	Point 7 2nd Drop
1	45.0	31.0	30.0	45.0	31.0	30.0	45.0	31.0	30.0	45.0	31.0	29.0
2	40.0	28.0	27.0	40.0	28.0	27.0	40.0	28.0	27.0	40.0	28.0	27.0
3	42.5	33.0	32.0	42.5	33.0	32.0	42.5	32.0	30.0	43.0	33.0	31.0
4	42.0	29.0	28.0	43.0	29.0	27.5	43.0	29.0	27.5	42.5	29.0	27.0

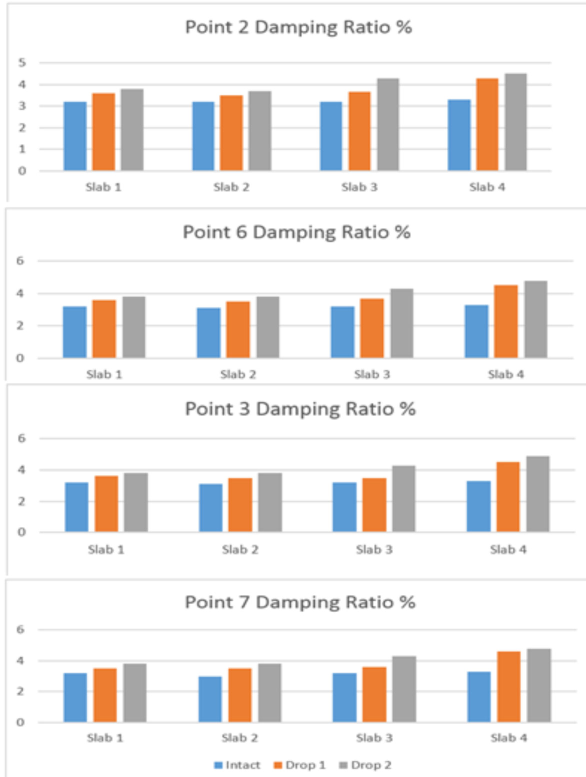


Figure 7: Mode 1, damping ratio for four slabs at four points (2, 3, 6 &7)

Figure 8: Mode 1, natural frequency for four slabs at four points (2, 3, 6 &7)

A decrease in natural frequency and increase in damping ratio was recorded due to damage of the concrete specimens as a result of dropped steel weight. The intense decrease in frequency after first drop about 25% is due to mobilization of reinforcements because of impact force. After second drop, the decrease in frequency is about 3-5%. Highest damping ratio is detected in slab 4 with lower reinforcement ratio which indicates more damage.

The intense increase of damping ratio in slab 3 after second drop is not related to more damage because there was no damage observed visually in form of cracks. This could be due to more internal friction caused by higher fiber content contributing with mobilization which enhanced the damping ratio (Giner et al. 2011). Higher damping ratio reduces vibration which is essential for health of structure.

8. CONCLUSIONS

The reliability of RD technique has been examined by comparing the fundamental natural frequencies of experimental tests and numerical models. The results of the RD successfully replicate the fundamental frequencies of tested UHP-FRC slabs with reasonable accuracy. RD is an effective technique for UHP-FRC slab monitoring for damage. An experimental study was performed on four UHP-FRC with different reinforcement ratio and fiber content to explore the suitability of RD technique to determine the existence and intensity of damage occurred by impact load. The test results revealed that the change in dynamic parameter by an increase in the damping ratio and a decrease in the natural frequency due to damage growth. To analyze the result of RD for identifying dynamic parameter, mobilization of reinforcement must be taken into consideration. As an additional conclusion, it has been observed that more steel fiber in the concrete mix did lead to more internal friction which enhance damping ratio.

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